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MULTI-SCALE ASSESSMENT OF GROUNDWATER VULNERABILITY TO POLLUTION: STUDY CASES FROM CAMPANIA REGION (SOUTHERN ITALY)

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EXTENDED ABSTRACT

La valutazione della vulnerabilità dei corpi idrici sotterranei all'inquinamento è di cruciale importanza per la gestione del rischio connesso al degrado qualitativo delle risorse idriche sotterranee, soprattutto nei paesi sviluppati ove l'intensa utilizzazione del territorio e la salvaguardia delle risorse idriche sotterranee sono di non facile compatibilità. Tale tematica è di particolare attualità nella regione Campania (Italia meridionale) per l'elevata dipendenza dalle risorse idriche sotterranee dell'approvvigionamento idropotabile, oltre che di quello termale, industriale, agricolo e geotermico (ALLOCCA *et alii*, 2007; ALLOCCA *et alii*, 2009), e dalla diffusa antropizzazione del territorio, che costituisce una potenziale fonte di contaminazione degli acquiferi. Pertanto, la prevenzione dei fenomeni di inquinamento delle falde idriche sotterranee è un obiettivo di fondamentale importanza per lo sviluppo socio-economico ed ambientale della regione, necessario da raggiungere anche per ottemperare alle prescrizioni della più recente normativa europea e nazionale in materia di tutela delle acque (Direttiva 2000/60CE; D.Lgs.152/2006).

Il presente lavoro si inserisce nell'ambito del progetto "Campania Trasparente", promosso dall'amministrazione regionale con lo scopo di valutare lo stato qualitativo delle principali matrici ambientali ed il loro impatto sulla qualità delle produzioni agricola e zootecnica. In particolare, lo studio presentato ha come obiettivo la valutazione della vulnerabilità all'inquinamento dei corpi idrici sotterranei, attraverso la costruzione di un geodatabase, implementato in un Sistema Informativo Geografico (G.I.S.), dalla cui elaborazione, attraverso metodi noti in letteratura e scelti ad hoc per le specifiche condizioni in esame, sono state prodotte cartografie della vulnerabilità all'inquinamento degli acquiferi a differenti scale spaziali. L'applicazione, sviluppo ed adattamento dei metodi di stima alle diverse scale spaziali è stato controllato dalla tipologia e densità spaziale dei dati disponibili in relazione alle differenti situazioni idrogeologiche, fisiografiche e di antropizzazione che caratterizzano la regione.

La sperimentazione è stata sviluppata in tre fasi di studio, consequenziali e reciprocamente interagenti, rispettivamente riferite alla scala regionale, alla scala del singolo acquifero e alla scala locale (o sito-specifica). Alla scala regionale è stato analizzato l'intero territorio della Campania (scala 1: 250.000), per il quale è stato applicato il metodo parametrico a punteggio e a pesi SINTACS (CIVITA & DE MAIO, 2000). Lo studio alla scala del singolo acquifero è stato focalizzato sull'acquifero carbonatico del Monte Terminio (scala 1: 50.000), per il quale sono state riconosciute particolari condizioni di vulnerabilità ed applicati differenti metodi parametrici, oltre il SINTACS, come il DAC (CELICO, 1996) ed il COP (VIAS *et alii*, 2006), specificamente idonei alla valutazione della vulnerabilità degli acquiferi carbonatici. Infine, alla scala locale, o sito-specifica, è stata valutata la vulnerabilità all'inquinamento da nitrati nell'area campione di Casalnuovo di Napoli-Volla, sita nel settore orientale della Piana Campana, che è stata ritenuta rappresentativa di acquiferi alluvionali con falda idrica sotterranea con bassa soggiacenza ed interessati da attività agricola intensiva. A tale scopo è stato applicato un modello numerico per la simulazione del trasporto nella zona vadosa e la valutazione dei tempi di arrivo dell'inquinante in falda.

I tematismi della vulnerabilità prodotti alle diverse scale rappresentano un valido strumento di supporto alla pianificazione territoriale finalizzata alla protezione delle risorse idriche sotterranee ed alla conoscenza del grado di protezione naturale delle stesse.

ABSTRACT

In the Campania region (southern Italy), assessment of groundwater vulnerability is an important factor to be tackled for a proper management of risk to aquifer pollution, which is fostered by both high dependence of aqueduct systems on groundwater resources and the widespread agricultural and urbanized land uses of the territory. The different physiographic, geological and hydrogeological conditions of the region, coupled with high anthropic pressure, make such assessment complex to be dealt with, but at the same time mandatory to be accomplished.

The proposed study has been developed into the framework of the "Campania Trasparente" project, which has been funded by the regional government to assess environmental factors controlling the quality of agricultural and livestock food productions. Specifically, it belongs to the research topic regarding the assessment of groundwater quality, with a special focus on the assessment of groundwater vulnerability.

In this research a multi-scale approach for the assessment of groundwater vulnerability is carried out in order to propose suitable methods depending on extension of territory to be studied and related types and spatial density of available data. Scales considered were a) regional, including the whole Campania region; b) intermediate, identified with that of a single representative aquifer; c) site-specific, or local, related to a portion of aquifer for which a high spatial density of data is available.The applied methods were chosen among the many known in literature and adapted to the specific study cases. At the regional scale, the parametric SINTACS method (CIVITA & DE MAIO, 2000) has been applied to the whole region and adapted to types and spatial density of available data. At the intermediate scale, or aquifer scale, the Mt. Terminio karst aquifer was chosen as representative for the application of different parametric methods, also specifically designed for karst aquifers. At the site-specific scale, a representative sector of a shallow alluvial aquifer, located in the adjoining Casalnuovo di Napoli-Volla municipalities, in the Campania plain, at the eastern border of the city of Naples, has been studied by numerical modeling for the estimation of travel time of nitrate pollutant through the vadose zone. The obtained results can be conceived as useful for supporting a proper territorial planning aimed at the management of risk to pollution of groundwater resources.

KEYWORDS: *aquifer vulnerability to pollution, groundwater resources, Geographical Information Systems, southern Italy*

INTRODUCTION

Following episodes of unlawful toxic waste disposal occurred in the last decade in few areas of the Campania region, the public opinion was induced to consider quality of agricultural and livestock food productions of the whole region as deteriorated. To assess the real state of environmental quality of the Campania region, the regional government has funded the "Campania Trasparente" project, to assess quality of environmental factors food productions. This study belongs to the branch of the "Campania Trasparente" project aimed at the assessment of groundwater quality, with a special focus on assessing groundwater vulnerability. In the Campania region (southern Italy), as in other parts of the world, groundwater resources are largely exploited for drinking, industrial and agricultural uses as well as to produce geothermal energy (ALLOCCA *et alii*, 2007).

Given the extreme relevance of these resources and their vulnerability to overexploitation and pollution, European and national laws have been issued for their safeguard and protection (Directive 2000/60/CE; D. Lgs. 152/2006). Generally, activities aimed at groundwater protection can be carried out at different scales, from that of the entire aquifer, or aquifer system, to the site-specific one, which are both based on extensive and in-depth knowledge of vadose zone and aquifer properties and aimed at the assessment of groundwater vulnerability to pollution.

Since the late 1970's, different methodological approaches were proposed in literature for assessing groundwater vulnerability, which can be grouped into three basic categories: i) methods based on the identification of homogeneous hydrogeological complexes and settings (ALBINET & MARGAT, 1970; BRGM, 1970); ii) parametric system methods, which are differentiated in matrix systems (GOOSSENS & VAN DAMME, 1987), rating systems (GOD - FOSTER, 1987; AVI - VAN STEMPVOORT *et alii* , 1993) and point count system models (DRASTIC – ALLER et alii, 1987 SINTACS – CIVITA & DE MAIO, 2000 and EPIK - DOERFLIGER & ZWAHLEN, 1997); iii) numerical models aimed at simulating the transport and attenuation processes of a pollutant through the vadose and saturated zones. This work deals with the experimental application and development of different methods, suitable to different scales and density/quality of data, which are represented by cases study of the Campania region, with different hydrogeological and anthropic features.

THE MULTI-SCALE APPROACH

The assessment of groundwater vulnerability was carried out through a multi-scale approach, in order to perform an adaptable evaluation to be dependent on type and spatial density of available data. The multi-scale study was divided into three consequential and interacting phases, respectively identified with regional, single aquifer and site-specific scales. The first phase of the study has been focused on the assessment of groundwater vulnerability of the entire Campania region with the scope to identify the most vulnerable aquifers as well as the vulnerability grade of the others. Following, given its regional

relevance, the Mt. Terminio karst aquifer was studied in the second phase for the assessment of its specific vulnerability to pollution. This aquifer, which is located in the Mts. Picentini Regional Park, represents a strategic groundwater resource for drinking use in southern Italy.

Finally, the third phase of the research was focused on estimating aquifer vulnerability of a representative shallow alluvial aquifer, which is exposed to intensive agricultural practices, based on the use of nitrate fertilizer (DUCCI *et alii,* 2017*)*. The sample aquifer corresponds to territories of the adjoining Casalnuovo di Napoli and Volla municipalities, which are located in a sector of the Campanian Plain at the eastern border of the city of Naples. In this case, groundwater vulnerability has been assessed by the estimation of travel time of pollutant through the unsaturated zone by a coupled numerical and empirical model applied to the site-specific scale.

STUDY AREAS

The Campania region (southern Italy) (Fig.1) is characterized by a complex geological and structural settings that control groundwater circulation, from the regional to local scales. The major geological structure of the Campania is an important sector of the southern Apennines, which consists of tectonic units piled up and folded during the Miocene orogenetic phases, forming mountainous and hilly morphologies of the eastern side of the region. While in the western side, the Campania region is characterized by alluvial plains filled by alluvial and pyroclastic products erupted by the most important volcanic centers, which were active during the Quaternary. In this regional geological framework, it is possible to identify four hydrogeological domains: 1) Quaternary alluvial and epiclastic deposits; 2) Quaternary volcanic products; 3) Mesozoic carbonate and dolomitic series; 4) Meso-Cenozoic turbidite and basin series. The Mesozoic carbonate and dolomitic series forms the major mountain ranges and regional aquifers which host huge groundwater bodies and represent the most strategic resources for socio-economic development of southern Italy (DE VITA *et alii* , 2018; ALLOCCA *et alii*, 2014).

In such a framework, the second area of study is the Mt. Terminio karst aquifer, which is one of the most representative karst aquifers of the Campania region. It is almost totally formed by Cretaceous limestones and dolomitic limestones and confined by aquitards or aquicludes formed by flysch and basin series (CELICO,1983; ALLOCCA *et alii*, 2007). The specific groundwater yield of the Terminio aquifer, estimated in about 0.045 m^3 s km^{-2} is among the highest for the karst aquifers of the Mediterranean area. This high productivity is originated by high permeability of the "pyroclastic soil-epikarst-carbonate bedrock" system, mean precipitation up to about 1500 mm/year and extended endorheic areas, which favour groundwater recharge. Groundwater circulation outflows in four huge basal springs: Cassano Irpino, Serino, Sauceto-Lagno and Baiardo. The location of the main springs, the geological settings and structural features allowed to identify four main groundwater basins (CELICO, 1978), which are reciprocally interconnected.

The third area of study is located in a sector of the eastern plain of Naples, with an extension of about 14 km^2 and corresponding to territories of the adjoining municipalities of Casalnuovo di Napoli and Volla. This area is part of the Pliocene-Pleistocene structural depression (graben) of the Campanian Plain, which was characterized by intense volcanic activity of Phlegrean Fields (60 kyrs – 1538) and Somma-Vesuvius (39 kyrs – 1944) volcanoes. In addition, during the Pliocene-Pleistocene period, alluvial, marine and fluvio-palustrine sediments filled this tectonic depression, producing a pyroclastic-alluvial plain characterized by a high litho-stratigraphic heterogeneity (BELLUCCI, 1998).

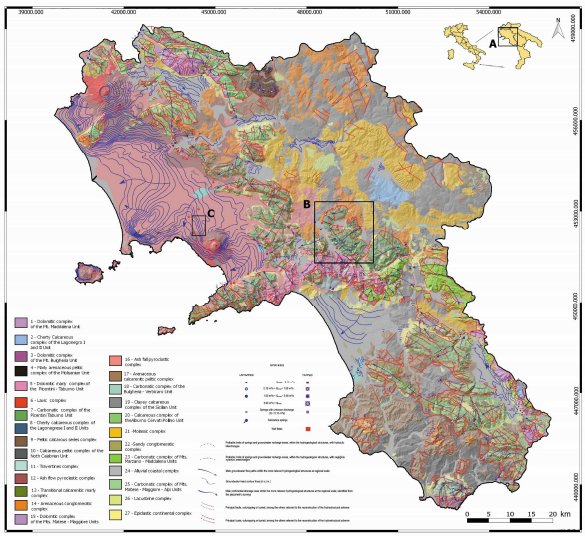

Fig. 1 - Study areas: A) Campania region; B) Mt. Terminio karst aquifer; C) Casalnuovo di Napoli – Volla alluvial aquifer (excerpt from the "Hydrogeological map of continental southern Italy" DE VITA et alii, 2018).

DATA AND METHODS

The groundwater vulnerability at the regional (1:250.000) and at single aquifer (1:50.000) scales was estimated by parametric methods, based on the following data:

- Hydrogeological map of continental southern Italy (DE VITA *et alii*, 2018);
- Digital Elevation Model (resolution 20 × 20 m);
- Soil type map of the Campania region (DI GENNARO, 2000);
- Corine Land Cover (2009);
- Discharge and altitude data of the main basal springs; Annual Groundwater Recharge Coefficient (AGRC); mean annual precipitation data and air temperature (ALLOCCA *et alii*, 2014);

- Updated geological maps (1:50.000) of the CARG Project (ISPRA): N◦ 449 Avellino; N◦ 450 Sant'Angelo dei Lombardi; N◦ 467 Salerno; N◦ 468 Eboli, used for the study of the Mt. Terminio karst aquifer.

In order to assess groundwater vulnerability to pollution at the regional and single aquifer scales, SINTACS-R5 method (CIVITA & DE MAIO, 2000) was applied. It is based on assigning a score to seven parameters: 1) depth to water; 2) net recharge; 3) aquifer media; 4) soil media; 5) topography; 6) impact of the vadose zone; 7) hydraulic conductivity. A score varying from 1 to 10 is assigned depending on local value of parameters. Moreover, the method is based on five lines of multiplying weights: 1) normal impact; 2) severe impact; 3) drainage (by stream); 4) karst aquifers; 5) fissured aquifers. The SINTACS index, expressing groundwater vulnerability, is given by the sum of products of scores, assigned to each parameter, and the associated weights. Moreover, for the karst aquifer of Mt. Terminio, the parametric methods of DAC (CELICO, 1996) and COP (VIAS *et alii*, 2006), specifically designed for karst aquifers, were also applied. At the site-specific scale, travel time of nitrate fertilizer pollutant through the vadose zone, considered as a proxy of groundwater vulnerability, was estimated by VS2DTI code, which is a physically-based model of variably saturated subsurface flow in two dimensions (HSIEH *et alii*, 2000). Modeling of travel time through the vadose zone was carried out on representative hydro-stratigraphic models of the test area down to a depth of 20 m, considered as the deepest value of water table occurring in alluvial aquifer. At this scope, hydro-stratigraphic data were considered to define several representative conceptual models of soil types which characterize the study area. At this scope, stratigraphic data derived from boreholes carried out in the study area (ALLOCCA *et alii*, 2016; CODA *et alii*, 2019) were considered as well as maps of water table depth, reconstructed by piezometric measurements in different periods. Rainfall and air temperature data from September 2003 to August 2013, recorded by the regional agro-meteorological network of the Campania Region (Centro Agrometeorologico Regionale - C.A.R.; station ID# Marigliano), were used to simulate hydrological response of the unsaturated zone in 10 consecutive hydrological years. Finally, the daily evapotranspiration rate was estimated using the Hargreaves's equation (HARGREAVES & SAMANI, 1985; ALLEN *et alii*, 1997).

RESULTS

Regional Scale

Results of the SINTACS index (Fig.2), computed at the regional scale, range between 58 and 247 and has been classified in six classes of groundwater vulnerability: very low, low medium, high, elevated and very elevated. As a general result, the Campania region is characterized by all groundwater vulnerability classes due to great extension of the territory and its different hydrogeological features (Fig.1.A). Specifically, calcareous and alluvial hydrogeological complexes are characterized by a high degree of vulnerability, while dolomitic complexes vary between the medium and high classes. Volcanic hydrogeological complexes are characterized by the very high class of groundwater vulnerability. Turbidite and basin series hydrogeological complexes results with groundwater vulnerability ranging between medium and high classes. Finally, hydrogeological complexes formed by argillaceous basin series result with a very low degree of groundwater vulnerability.

Aquifer Scale

A detailed hydrogeological map, 1:50.000 scale, has been reconstructed on the basis of the updated geological maps, obtained by the CARG Project (ISPRA). Moreover, by new stratigraphic data obtained by boreholes, carried out in inner parts of the Mt. Terminio karst aquifer, new piezometric head data were achieved. The latter, joined with other piezometric head data related to main basal main springs and well fields, allowed to reconstruct piezometric contour lines of the basal groundwater circulation. Consequently, a new groundwater circulation scheme, subdivided in four groundwater basins with different hydraulic gradients, was reconstructed considering also directions and principal divides of groundwater, generally represented by faults. Finally, a hydrological budget was carried out for each groundwater basin, allowing to validate hypothesis regarding the extension of the four groundwater basins. The achieved SINTACS aquifer vulnerability map (Fig.3) allowed to consider the Mt. Terminio karst aquifer as mainly characterized by two classes of groundwater vulnerability, varying between the medium and high grades (79.7% and 18.2 % of the entire area, respectively). High and extremely high classes of groundwater vulnerability (1.6% and 0.4% of the entire area respectively) were found in the Sabato river plain and in that surrounding the Serino springs, both due to the shallow depth of the water-table.

Local Scale

Among the most important results regarding modelling travel time of nitrate pollutant through the vadose zone, hydraulic conductivity and soil pressure head were found as strongly controlling the velocity of movement. In detail, modelling shows that pollutant water propagates downward with yearly concentration waves, depending on local regime of precipitation, which decrease their amplitude and increase their length with depth. In addition, this behaviour shows daily concentrations of pollutant characterized by higher peaks close to ground surface (down to a depth of 2.50 m). As above starting

from 3.50 m of depth, down to the depth of 20 m, the distribution of pollutant was characterized by smoothed and delayed peaks. Travel time of the pollutant through the vadose zone was found to be controlled by depth to water table and saturated hydraulic conductivity. Moreover, an empirical correlation among estimated travel time, depth to water table and equivalent hydraulic conductivity of the unsaturated zone was found. Starting from maps of water table depth and equivalent hydraulic conductivity, such a correlation allowed to estimate a map of travel time for the studied area. Finally, the range of arrival time values was classified identifying and mapping five classes of groundwater vulnerability (Fig. 4). Results showed that the shallow pyroclastic-alluvial aquifer is affected by different vulnerability degree to nitrate pollution, according with results of other studies. Specifically, the Casalnuovo-Volla test area may be divided in two main areas affected by opposite vulnerability classes. In detail, both northern and central-southern sectors are characterized by medium vulnerability class due to the hydrogeological setting characterized by pyroclastic and alluvial alternating soils, while two areas in the central sector of the study area are characterized by higher groundwater vulnerability classes. These areas coincide with the sector with the lowest depth of water table and soils of the vadose zone with higher hydraulic conductivity. The remaining sectors of the study area, characterized by deepest or semi-confined groundwater conditions, are affected by very high travel times, thus characterized by very low vulnerability degree.

CONCLUSIONS

This paper advances the assessment of groundwater vulnerability in a complex hydrogeological framework,represented by the Campania region, by using a multi-scale approach, from regional, to single aquifer and to site specific scales.

The regional scale analysis allowed to define a large variability of groundwater vulnerability due to the complex hydrological, morphological and anthropic conditions. Results identify the alluvial, calcareous and volcanic hydrogeological complexes as the most vulnerable, the dolomitic as the least and the turbidite one as the most variable. Such results are useful for improving a proper regional territorial planning aimed at the protection of groundwater resources. The Mt. Terminio karst aquifer, studied as representative for the aquifer, or intermediate scale, is mainly characterized by a medium groundwater vulnerability, although the "pyroclastic-alluvial soil carbonate bedrock" system is the most vulnerable, due to its high permeability. In this phase, hydrogeological knowledge of the study aquifer was advanced by the reconstruction of an updated hydrogeological map and a new groundwater circulation flow scheme. Considering that in Italy, and especially in southern Italy, karst aquifers constitute the main source of drinkable water, results achieved can be considered as reference case study for assessing groundwater vulnerability of other karst aquifers aimed at the preservation of the groundwater quality. Finally, the site-specific study of the shallow alluvial aquifer of the Casalnuovo-Volla municipalities sample area, which is representative of a large part of plain areas of the Campania region, also for intensive agricultural practices and use of nitrate fertilizers, represents also a reference case of study for similar hydrogeological and anthropic conditions. The approach used are to be considered applicable in limited areas for which a high spatial density and quality of hydrogeological data are available. The approaches used can be conceived as applicable in any other complex and time-changing hydrogeological settings (seasonal hydrological variations, annual groundwater recharge alteration and climatic changes) and anthropic impact conditions, such as different land uses, over-exploitation of groundwater resources with lowering of water table levels and groundwater rebound (CODA *et alii*, 2019) related to the abandoning of groundwater pumping.

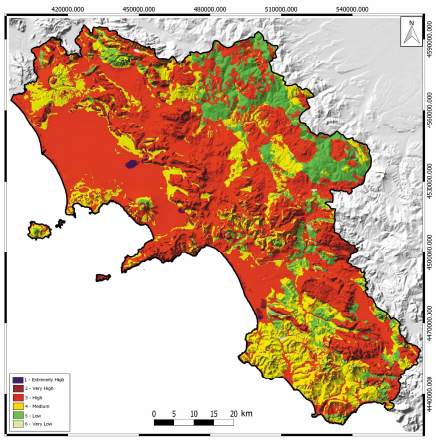

Fig. 2 - SINTACS vulnerability map (1:250.000 scale) of the Campania region.

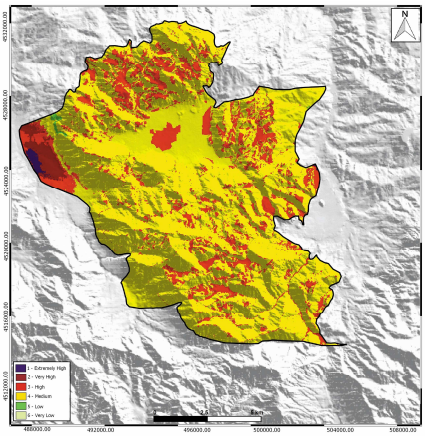

Fig. 3 - SINTACS vulnerability map (1:50.000 scale) of the Terminio karst aquifer.

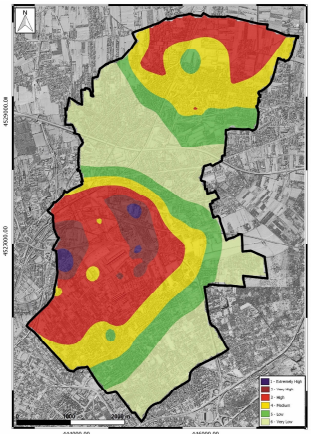

Fig. 4 - Vulnerability map to nitrate pollution of the Casalnuovo – Volla alluvial aquifer.

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